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Plitvice Lakes

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Preface

Plitvice Lakes (Croatian: Plitvička jezera) are a remarkable ecosystem on a global scale, exceptional in a diversity of almost all environmental aspects—climate, hydrology, geology, geography, and biology—from frozen to warm, from flooding to drying channels, from springs to lakes, from dolomite to limestone, from valley to canyon. This edition aims to compile the research done so far in all these aspects, and all focusing toward understanding the exciting interplay of these factors.

The interplay of all these factors results in some of the most exciting and beautiful landscapes that have developed through the phenomenon of calcite precipitation—tufa deposition. Very soluble carbonate rocks readily dissolve in precipitates and in the underground. Since precipitation is (was) abundant, plenty of springs developed that formed the stream system. When the underground water, supersaturated with respect to calcium, bicarbonate, and carbonate ions and slightly acidic due to excess dissolved carbon dioxide, reaches the surface, the carbon dioxide outgasses, shifting the equilibrium of carbonate and calcium toward crystallization at appropriate places. These are the tufa barriers. They are the main phenomenon of this ecosystem. The barriers form seemingly randomly but from current knowledge, they are the result of changes in water flow dynamics, and biota that develops at these sites—mainly autotrophs. Both help evacuate carbon dioxide even further and facilitate the deposition of crystals. This process formed lakes and waterfalls over some 300 000 years.

Tufa is a calcium carbonate deposit that developed in supersaturated waters of karstic origin. The mineral crystals are deposited on (as opposed to within) organic tissue. Mosses, algae, and even invertebrate cases or exuviae comprise a significant part of the tufa depositional frameworks. Even though this process is known in other places, at Plitvice lakes it is dramatically fast with a rate of growth of approximately 1 cm per year at places.

This exciting ecosystem has attracted scientific attention since mid-late nineteenth century. The peak of interest that resulted in the proclamation of this area a National Park was through the work of a Croatian botanist Ivo Pevalek. Plitvice Lakes received international recognition in 1979, by being included in the UNESCO World Heritage List.

Among numerous fans of the area and scientific researchers, Pevalek was the first that wrote about his discoveries that water mosses and algae are crucial for the unique geomorphology of Plitvice Lakes. Subsequently, many of freshwater ecologists have studied and worked in this exceptional ecosystem. We all had a great time and are continuing to having it.

It is our profound pleasure to present the works of the great researchers past and present that made this book possible.

Zagreb, Croatia

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Geomorphological and Geological Properties of Plitvice Lakes Area

Neven Bočić, Uroš Barudžija, and Mladen Pahernik

Abstract Plitvice Lakes are a world-famous karst phenomenon. Their origin and development is a consequence of a specific geological structure and geomorphological processes. The aim of this chapter is to provide an overview of geoscientific knowledge about this area with additional data from recent research. This area belongs to the outer Dinarides, the largest karst area in Europe. The majority of geological material consists of Triassic dolomite, Jurassic dolomites and limestones, and Cretaceous limestones. Differences in lithology also cause differences in hydrogeological characteristics and in exogenous geomorphological processes. Areas built of dolomite are mostly impermeable, so a drainage network and erosion processes have been developed on them. Karstification processes predominates on the limestones and there are lack of the surface streams. The most famous phenomena are tufa barriers and a series of cascading barrage lakes with waterfalls that make this area world famous.

Keywords Karst · Fluvio-karst · Karst geology · Karst geomorphology · Karst lakes · Karst rivers · Plitvice lakes · Croatia · Dinaric karst

1 Introduction

The Plitvice Lakes National Park was declared on April 8, 1949, covering an area of 192 km^2. Since 1979, the Plitvice Lakes National Park has been on the UNESCO

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World Heritage List. This confirms the uniqueness and global significance of this phenomenon. In 1997, the area of the National Park was expanded and now covers an area of 295 km^2.

Due to their exceptional value, the Plitvice Lakes have been the subject of research by numerous researchers. As this is a world-famous karst phenomenon, numerous geomorphological and geological researches have been carried out. One of the oldest known descriptions of the area of Plitvice Lakes with a hypothesis about their origin is given by the geographer Milan Šenoa (Šenoa 1895). The first known geomorphological surveys were carried out by Hranilović (1901) and Gavazzi (1903). Also, detailed descriptions of this area with an explanation of origin of the lakes are given by Hirc (1900) and Franić (1910). Poljak (1914) gives a detailed overview of the previously known caves and pits of this area. Pevalek (1925/26) writes about the geological significance of tufa deposits. First detailed geological investigations in the Plitvice Lakes area were performed by Koch (1916, 1926, 1932), who made the first geological map in the scale of 1:75.000 and defined Cretaceous carbonate rocks as predominant in the area. Later, Kochansky-Devide (1958) and Polšak (1959, 1960, 1963) performed geological and biostratigraphic research in the area and distinguished Triassic, Jurassic and Cretaceous rocks. Roglić (1951, 1958, 1974) analyzes the geomorphological features and the formation of the Plitvice Lakes. A detailed overview of caves and pits is given by Rendešek (1958), and Polšak (1974) writes about the geological aspects of the protection of the Plitvice Lakes. By basic geological mapping in the scale of 1:100.000 performed in the second half of the twentieth century, Bihać (Polšak et al. 1976) and Otočac (Velić et al. 1970) sheets of the Basic Geological Map were produced. These sheets were the basics for Geological Map of Croatia in 1:300.000 scale (HGI-CGS 2009), on which basic lithostratigraphy (Velić and Vlahović 2009) in the Plitvice Lakes area can be observed. Srdoč et al. (1985) publish a detailed study on calcite deposition, and Horvatinčić et al. (2000, 2003) provide data on the age of tufa. Explaining the conceptual hydrogeological model Biondić et al. (2010) also give a hypothesis of the origin of the Plitvice Lakes. Overview of geomorphology was also given by Bočić (2009) and lithostratigraphy by Barudžija (2014). More recent contributions on tectonics and structural relations in the Plitvice Lakes area were given by Krnjak et al. (2019).

Plitvice Lakes are located (Fig. 1) between Mala Kapela (1279 m) in the west and northwest, Lička Plješivica (1646 m) in the southeast, Lika highlands with karst fields in the south and Una-Korana karst plateau in the northeast. A series of 16 lakes that generally stretch from south to north are an integral part of the Korana River valley. The southernmost Lake Prošće is the highest (636 m) while the northernmost lake, Novakovića Brod, is the lowest (503 m) in the series of the Plitvice Lakes. The area of the National Park is built of carbonate rocks of Mesozoic age, and according to the lithological characteristics, several units can be distinguished that have different hydrogeological and geomorphological features.

The aim of this chapter is to give an overview of previous knowledge about the geological structure and geomorphological features and their connection in the area of the Plitvice Lakes National Park. The review has been supplemented by more recent, primarily morphometric data.

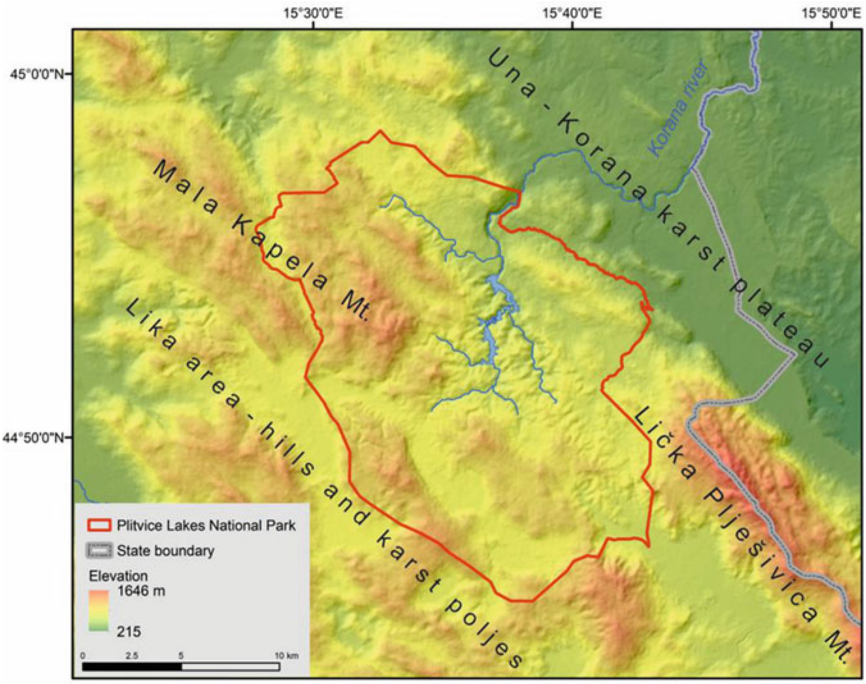

Fig. 1 Location and coverage of the Plitvice Lakes National Park in relation to the most important relief units

2 Bacis Geomorphometric Properties

Morphometric analyzes were made based on a high-resolution digital elevation model (0.5 × 0.5) obtained by airborne lidar scanning. The highest point of the entire area of the National Park is Seliški vrh (1279 m), the lowest is in the Korana canyon at 367 m and average height is 803.7 m.

The hypsometric map (Fig. 2a) indicates the basic orographic features of the terrain and suggests that the whole area consists of a north-eastern lower and a south-western upper part. The north-eastern part is a relatively flattened fragment of a karst plateau with a height range of 500–800 m. The lowest height is in the central part where the Korana canyon was cut, up to 150 m in relation to the level of the plateau. On the plateau itself there are some elevations, the highest of which are 867 and 889 m. Along the very northern edge of the park there is another series of relatively higher elevations. The south-western, higher part of the Park is much more heterogeneous. In its northern part is the highest elevation of the Park (Seliški vrh 1279 m) with the parallel ridge of Razdolje (1113 m). In the southern part, three main ridges extend along the dinaric orientation. Between the southeastern and midle series of ridges are two large karst depressions.

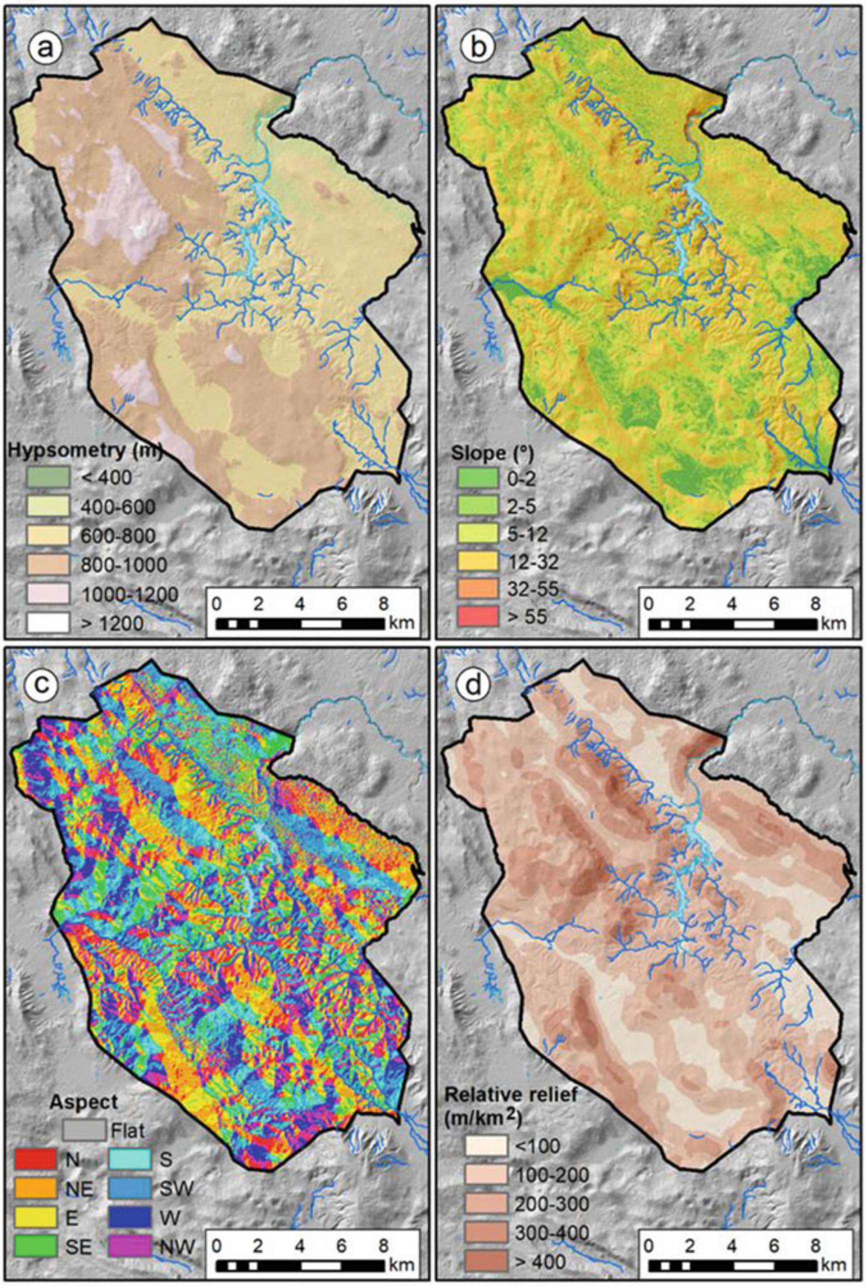

Fig. 2 Geomorphometric maps of the Plitvica Lakes National Park: **a** hipsometry, **b** slope inclination, **c** slope aspect, **d** relative relief per 1 km^2

The average slope of the whole terrain is 12.5° and the spatial distribution of the slopes (Fig. 2b) shows their spatial heterogeneity. As a rule, lower slopes are primarily related to the bottoms of larger karst depressions (uvalas and poljes) and to the karst plateau. Large slopes are associated with slopes along tectonic zones. These zones are elongated and straight, mostly with dinaric orientation (NW–SE). Along with them, large slopes are related to the zones of deep incision of the drainage network. The most pronounced examples are in the Korana canyon where the canyon cliffs are often subvertical and vertical.

The slope aspects show the orientation of the slope in relation to the sides of the world. This method is important because it can indicate morpholinaments resulting from active tectonics, but it also indicates the exposure of individual slopes to various exogenous influences. The map of slope aspects (Fig. 2c) indicates the predominant north-eastern and eastern orientations on the one hand, and south-western and western orientations on the other. Such slope orientations reflect the prevailing dinaric structures. It can also be noticed that the fragmentation of the slope orientation fields is significantly higher in the north-eastern part than in the south-western part, which is probably a consequence of the stronger karstification of the north-eastern part of the Park.

The relative relief was calculated as the difference between the highest and lowest point per unit area (1 km^2). The minimum recorded values are 11.3 m/km^2, the maximum is 440.1 m/km^2, and the average is 162.5 m/km^2. These values indicate a significant erosion potential, and indirectly tectonic activity, especially vertical movements. The map of relative relief (Fig. 2d) clearly outlines tectonic zones, mainly of Dinaric orientation. Similar to the slope, the smallest relative relief is related to the bottoms of larger karst depressions and to the plateau karst. The central, dinaric-oriented belt of increased values of relative relief is also noticeable, in which the Plitvice Lakes themselves developed.

3 Geological Properties

Basic geological properties are shown on geological map (Fig. 3) made on the basis of data of the section of the Geological Map of Croatia in 1:300.000 scale (HGI-CGS 2009).

3.1 Lithostratigraphy

The underground of the Plitvice Lakes is built of Triassic, Jurassic and Upper Cretaceous sedimentary rocks. All these rocks are almost exclusively carbonates (various types of limestones and dolomites), and the other sedimentary rocks are only subordinately present in the area. Upper Triassic deposits are almost exclusively well

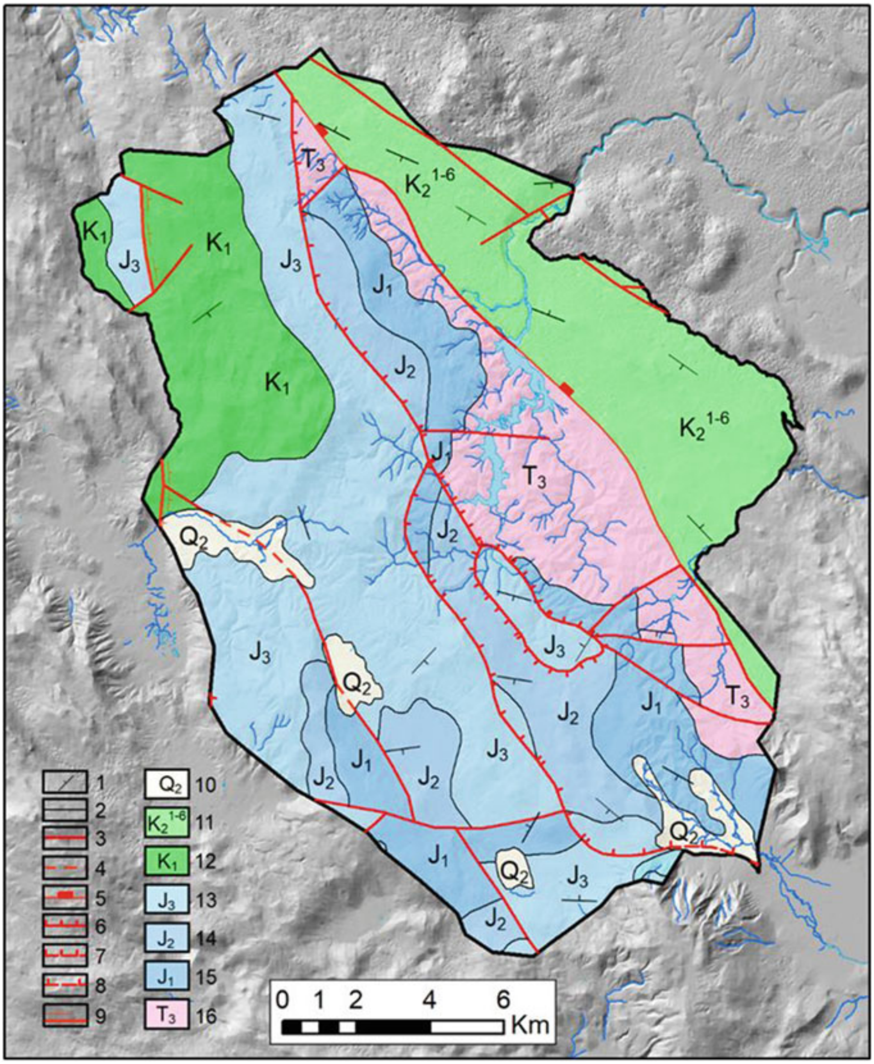

Fig. 3 Geological map of the Plitvice Lakes National Park area (partly modified after HGI-CGS 2009). Legend: 1-dip and strike of beds; 2-normal (continuous) contact of beds; 3-fault: determined; 4-fault: covered; 5-lowered block; 6-reverse fault: determined; 7-reverse fault: covered; 8-reverse fault: partly covered; 9-overthtrust: covered; 10-Holocene: deluvium and proluvium deposits; 11-Upper Cretaceous: limestones; 12-Lower Cretaceous: limestones and dolomites; 13-Upper Jurassic: limestones and dolomites; 14-Middle Jurassic: limestones and dolomites (thick bedded); 15-Lower Jurassic: limestones and dolomites; 16-Upper Triassic: dolomites

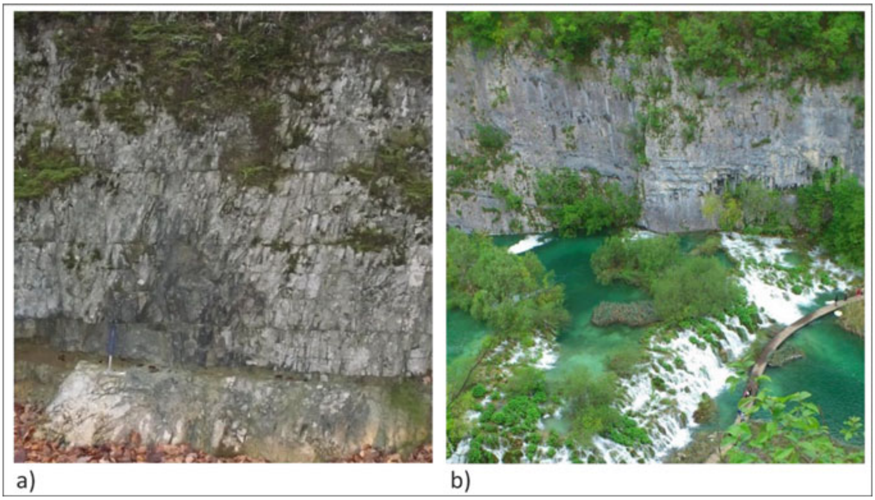

Fig. 4 **a** The Upper Triassic well bedded grey dolomites at banks of the Upper Lakes, **b** The Upper Cretaceous limestones in the canyon walls at the Lower Lakes. Photos by U. Barudžija

bedded grey dolomites (Fig. 4a). Lower Jurassic deposits are predominantly limestones, partly intercalated with dolomites. Middle Jurassic rocks are fossiliferous limestones (i.e. limestones with lithiotid bivalves), occasionally interlayered with thick beds of dolomites. Upper Jurassic deposits are well bedded limestones, occasionally with thin layers of dolomites and cherts. Lower Cretaceous deposits are represented by monotonous sequences of grey to brown coloured limestones. Upper Cretaceous well bedded to massive fossiliferous limestones often contain abundant fauna of rudist shells or its debris (Fig. 4b). Quaternary lake tuffa, which make the barriers and cascades of the Plitvice Lakes, are the youngest deposits in the area. These are highly porous grey or yellow rocks; whose total thickness occasionally exceeds 20 m.

3.2 Hydrogeology

The Plitvice Lakes are situated in the Outer Dinarides, within the karst hydrological regime having strong water circulation, complex subterranean interconnections, strong karst springs and confined lakes development at the surface. By combination of these factors complex hydrogeological mechanisms were formed, depending mainly on the permeability of the rocks and on their tectonic and structural relationships as well. Some of the rocks represent the barriers for water percolation and subsequently leads to the accumulation of water, while the other rocks allow water to circulate throughout. Depending to their permeability and ability to accumulate water, rocks are considered as permeable, low permeable or impermeable.

The impermeable barriers are the Upper Triassic dolomites as well as conformable Lower Jurassic limestones and dolomites. The Upper Triassic dolomites have low primary and slightly enhanced (due to dolomitization) secondary porosity, and they are generally considered as low permeable rocks. However, dolomites are considered also as impermeable barriers due to impermeable Upper Triassic (Carnian) clay layers below, which additionally prevent vertical water circulation. Cracks and fissures in the Upper Triassic dolomites are therefore well saturated and the water is accumulated and drained in numerous springs. Due to these impermeable barriers, surficial watercourses started to develop and flow, and the present-day Upper Lakes were eventually formed, almost without loss of water in the karst underground. Lower Jurassic impermeable carbonates with marls and chert interlayers additionally consolidate this barrier, preventing vertical water circulation. Another barrier for water circulation is the horizon of impermeable Upper Turonian platy to laminated clayey limestones, situated below heavily karstified rudist limestones. These impermeable rocks are responsible for water accumulation in the Lower Lakes area. Thick sequences of the Middle to Upper Jurassic and Lower Cretaceous limestones and dolomites, as well as the Upper Cretaceous rudist limestones, are mainly permeable rocks. The areas with these rocks are the main waterways due to various karst features developed within, such as dolines and caves. Water percolates mainly through the cavities, and it is drained from the underground at the springs located near the impermeable barriers.

3.3 Tectonics and Structural Elements

The folded and overthrusted Dinaric Mountains chain, part of which are also the Plitvice Lakes, originated by convergence of the Adriatic Microplate and the Euro-Asian Plate, since the Upper Jurassic until the present-day (Pamić et al. 1998; Vlahović et al. 2005; Schmid et al. 2008, with accompanying references). The oldest deposits in the External (Karst) Dinarides are of Carboniferous age, and succession of Palaeozoic, Mesozoic and Cenozoic predominantly carbonate deposits follows. These carbonates are genetically linked with the tectonic evolution of the Adriatic Microplate, and clastic deposits subordinately appear. In the Plitvice Lakes area Triassic, Jurassic and Cretaceous deposits are present. Among the structural elements, faults predominate, and the older folds can be seen as well. Main tectonic units stretching along the NW–SE strike. The Upper Triassic dolomites in the middle part of the terrain are delineated on the NE from folded Upper Cretaceous rudist limestones by almost vertical reverse fault. The Lower and Upper Jurassic rocks continues upon the Upper Triassic dolomites towards the SW. Faults with predominant NW–SE (so-called "Dinaric") strike prevail in the area (Polšak 1974; Polšak et al. 1976, 1978), and they originated in the Middle-Upper Eocene and Oligocene (Vlahović et al. 2005). These faults are later intersected by the faults with E-W strike, which enabled intense karstification and disintegration of the Mesozoic deposits (Herak 1955; Polšak 1959, 1960; Velić et al. 1970; Polšak et al. 1976, 1978, with accompanying references). After Polšak et al. (1978) and Velić et al. (1970), two regional tectonic units, Mala Kapela-Lička Plješivica and Lipovača-Cazin, are outlined in the Plitvice Lakes area. These regional units consist of small-scale structural units: Veliki Javornik, Brezovica-Krbavica, Plitvice Lakes, Trovrh-Gola Plješivica and Čatrnja-Lipovača.

4 Morphogenesis

4.1 Processes and Forms

The area of the Park is exogenously shaped by karst and erosion processes. The spatial distribution of the predominant influence of these processes primarily depends on the lithological structure of the terrain (Figs. 3 and 5). However, all exogenous processes are driven by a high energy of relief that significantly exceeds the local erosion base—the Korana River, which is within the Park at 367 m above sea level, but on the nearby Una-Koran Plateau is even lower, at about 320 m (Fig. 1). Such orographic relations are also a consequence of tectonic movements, mostly the relative uplift of this area in relation to the erosion base in the northeast.

The most characteristic karst form of this area are dolines. These circular and subcircular depressions can be considered as a diagnostic form of karst (Ford and Williams 2007). Based on the topographic map at a scale of 1: 25,000, 7238 dolines were singled out in the Park area. As previous experiences show that due to generalization, these maps show about 50% of all existing dolines, we can assume that there are about 15,000 of them in the Park area. The spatial distribution (Fig. 5a) and dolines density (Fig. 5b) are very uneven. There are areas without them while the maximum density is 113.7 dolines/km^2, which falls into the category of very high density of dolines (Pahernik 2012). The average density for the entire area of the Park is 24.1 dolines/km^2. The main factor of this spatial distribution is the difference in lithology (Pahernik 2012). Most of them are in the area built of Upper Cretaceous limestones. This is confirmed by the data obtained from the Lidar high resolution digital elevation model. In the area made of Upper Cretaceous limestones, the average density of all dolines was measured as high as 156.15 dolines/km^2. In addition to lithology, the slope inclination also plays an important role in the spatial distribution of dolines. This is particularly pronounced in the highest parts of the park which, although lithologically quite homogeneous (Lower Cretaceous limestones), have a heterogeneous distribution of dolines. They mainly appear on slopes of small and medium inclination, while on steep slopes they are absent.

In addition to dolines, large karst depressions also occur in this area (Fig. 5c). The largest are located in the southern part of the Park. These are the shallow karst uvala Mačje doline (2.7 km^2), the Homoljačko karst polje (4.7 km^2) and the largest karst depression in the Park-Brezovac (4.7 km^2). In the northern part of the Park, the karst uvala Štropovi (1.8 km^2) stands out, which is the deepest karst depression of the Park with a depth of 90.1 m. There are no major depressions in the northeastern part of

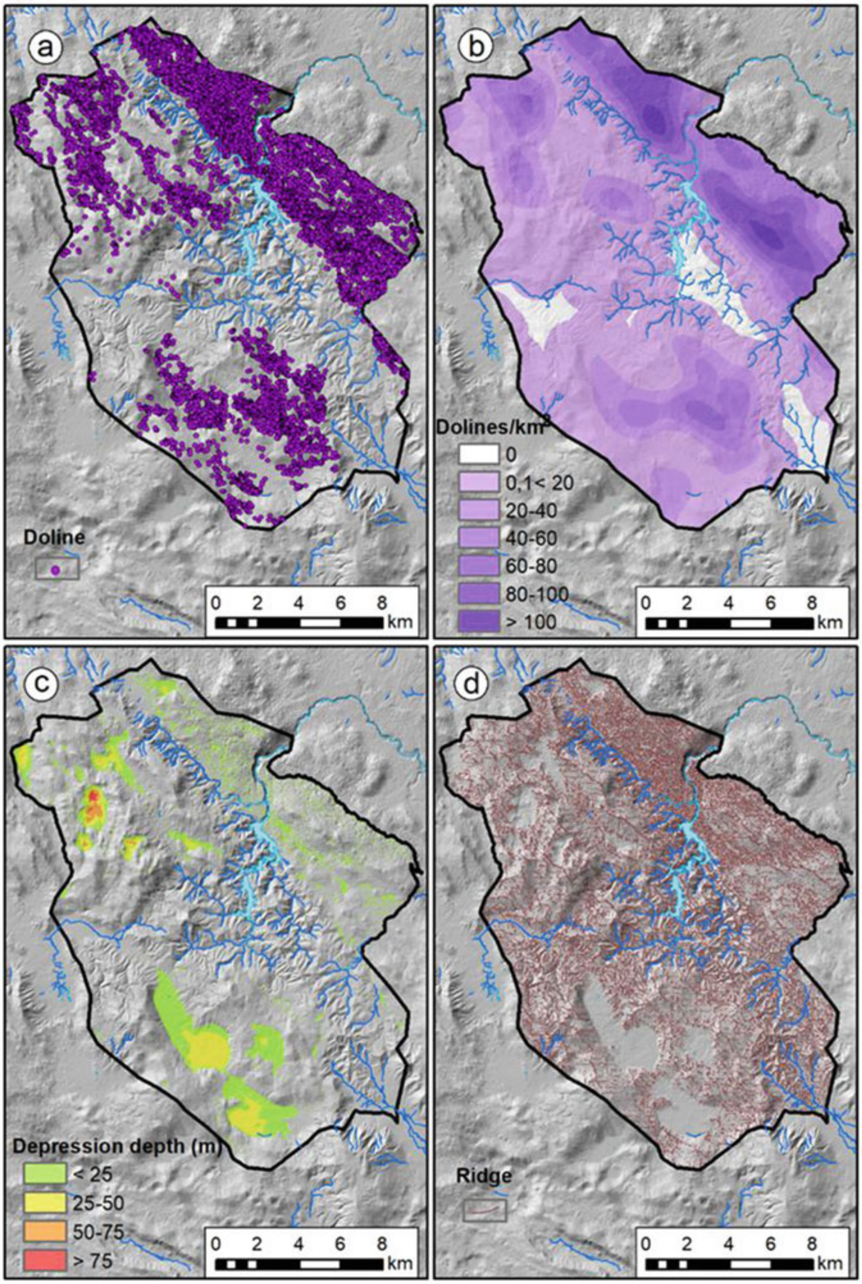

Fig. 5 **a** Spatial distribution of the dolines, **b** dolines density, **c** spatial distribution and depth of karst depressions, **d** spatial distribution of ridges

the Park because it is a karst plateau. It is assumed that this plateau is an elevated fragment of a large Una-Korana plateau (Bočić et al. 2010, 2015).

The area of the National Park is rich in numerous underground karst phenomena—caves. About it see in a separate chapter of this book (Miculinić et al. 2022).

In areas built of dolomite, mechanical erosion predominates, and thus the development of a surface drainage network (Fig. 5a). Such relief is most developed on the impermeable Upper Triassic dolomites as well as Lower Jurassic limestones and dolomites. The most significant relief forms of this area are gullies and valleys. The valleys are relatively short. The longest valleys are Sartuk and Plitvice (9.2 km), Riječica (6.3 km), Bijela rijeka and Matica (5.5 km), Draga (4.8 km) and Crna rijeka (3 km). They have steep sides, mostly have a V cross-section and mostly deeply cut into the surrounding terrain (often over 100 m). The flat valley bottom with accumulated material appears only sporadically (e.g. the valley of Bijela rijeka and Matica). Numerous gullies, ravines and smaller valleys with rather strong erosion appear in the valley heads and valley sides. Although morphologically this relief is most similar to the valley type (fluviodenudational) due to the carbonate structure and the karst solution present in the total denudation, it is actually a fluvio-karst on the dolomites. In addition to dolomite fluvio-karst, some forms of contact fluvio-karst (Gams 1986; Mihevc 1991) are present here, such as pocket valleys, dry and blind valleys. The most pronounced pocket valley is the amphitheatre depression around the source of the Plitvice stream with steep slopes higher than 150 m. Also, parts of the hydrographic network that have been cut in the limestone terrains have canyon-type valleys and gorges. The most pronounced example is the canyon in which the Lower Lakes are located, then the canyon of the river Korana and parts of the valley of Sartuk and Plitvice.

There are also positive forms that are primarily associated with ridges (Fig. 5d). The highest and most emphasized are the ridges that were formed as a result of structural relations, and they are here related to higher elevations, namely the dinaric orientation. The denudation ridges are much more common, representing slower denuded parts of the terrain between depressions. In the terrain with predominant karst denudation, the ridges are of higher density and close the polygons around dolines and other karst depressions. In the part of the terrain with pronounced surface erosion, the ridges are somewhat rarer and represent local watersheds between valleys and deep gullies.

In addition to denudation forms, the processes of material accumulation also play an important role in the morphogenesis of this area. Along with the alluvial end proluvial fans, sporadic alluvial deposits and colluvial forms on the slopes, the most significant accumulation forms of this area are tufa deposits. This is the most recognizable phenomenon of this area, and at the same time the main cause of the fundamental phenomenon of the Park—the lakes and waterfalls themselves.

Tufa is formed by crystallization of calcium carbonate, i.e. calcite from water (for details see Sironić et al. 2022; Matoničkin Kepčija and Miliša 2022). It consists of hollow, extremely porous limestones formed on the waterfalls of karst rivers and lakes and on springs. Calcite crystals are excreted from water in certain physico-chemical conditions and are caught on rocks, moss, aquatic plants and submerged trees by means of algae and bacteria. Such sedimentation creates tufa barriers over which water flows from a higher lake to a lower one. In this way, one of the most important landscape phenomena in the Park is created—numerous waterfalls. As the barriers rise, the water level in each lake also rises. The tufa barriers of the Plitvice Lakes are very complex morphologies, and 15 large complexes of tufa barriers are grouped. A study of the age of the Plitvice Lakes tufa showed that the current active barrier began to form before about 6–7 ky. Tufa was also found in the area of the Park in paleobarriers aged 90–130 and 250–300 ky (Horvatinčić 1999; Horvatinčić et al. 2000). It has also been found that the growth rate of tufa barriers is different and when the downstream barrier grows faster, the lake can submerge the upstream barrier. Such submerged barriers have been found, for example, in Lake Kozjak. In periods favorable for their growth, tufa barriers created barrage lakes, which become depression favourably for sedimentation. Slowing down the water flow and sedimentation processes reduces the erosion impact of the stream on the deepening of the riverbed. When climatic conditions are unfavorable for the growth of tufa, conditions are created for increased erosion of tufa formations, lake sediments and the bedrock itself. Tufa barriers and barrage lakes also have an impact on the water level in the riverbed, i.e. on the local erosion base that defines the incision of the surrounding valleys and gullies. It also has an impact on the groundwater level, i.e. the local karstification base.

4.2 Relief Development

The development of the relief, and especially the origin of the Plitvice Lakes, has not been sufficiently researched to date. Only a few works try to give an explanation of the origins of this area while giving different interpretations. Nevertheless, all the proposed hypotheses can be classified into two groups. The first is that the Upper Lakes depressions were primarily formed in which lakes were created later by the accumulation of water from endoreic watershed. Only later, there was a cascading overflow of water into lower depressions and the final creation of the Korana river valley as an effluent (outflow) river. Šenoa (1895) and partly Hranilović (1901) supported this hypothesis, believing that depressions were primarily of karst, i.e. exogenous origin. Koch (1926), on the other hand, believed that lake depressions were formed as a result of folding, so the larger Upper Lakes developed in syncline depressions. Biondić et al. (2010) also belong to this group of hypotheses, they believe that Lake Prošće and Lake Kozjak basins were formed as tectonic depressions. Initially, the higher lake was created in such depression—Prošće, and then there was an overflow of water into the lower Lake Kozjak.

The second group of hypotheses (e.g. Gavazzi 1903, Roglić 1951, 1958, 1974) starts from the fact that a surface drainage network was originally created whose backbone is the valley of the former course of the Korana. With the formation of tufa barriers, the valley was partitioned and cascading barrage lakes were created. The difference in the morphology of the Upper and Lower Lakes is explained by the difference in the lithological background. The part of the valley in which the Upper Lakes were formed was developed in dolomite, in which, due to more intensive weathering, the valley sides became flatter, and the valley itself became wider. In contrast, the Lower Lakes were formed in limestone, so the valley itself has a canyon morphology. Based on the geomorphological, especially morphometric features of the relief; we are currently more inclined to adhere to the second hypothesis of partitioning a previously developed valley, although there are still a number of open questions. According to currently known data, we believe that the development scenario was approximately the following.

Due to the described hydrogeological conditions, surface watercourses with the direction of runoff towards the north or northeast were primarily formed in this area. Due to the neotectonic uplift of the area of Mala Kapela and Lička Plješivica, there was an increased incision of the main watercourse—Korana. The incision was made possible by the large gradient and consequently the erosion force of the river, but also because the bedrock was tectonically fractured. In the zone built of dolomite, a wide and mild valley with numerous surface tributaries was formed, while the downstream part of the valley in the area built of limestone took the form of a steep and deeply incised canyon without surface tributaries. The surrounding area was exposed to intensive karstification and the development of underground karst hydrography. The strong incision of the Korana canyon is also evidenced by the 76 m high waterfall with which the Plitvica Stream flows into the Korana valley. Due to favorable conditions for tufa formation, tufa barriers began to block the Korana Valley and thus create series of lakes in the valley. The difference in the shapes of the lakes thus formed is defined by morphological differences along the submerged valley. The Upper Lakes were formed by flooding of the part of the valley incised into the dolomite base, so they are wider and more spacious and with slightly inclinated shores. The Lower Lakes were formed by the flooding of a canyon valley incised into limestone, so they are therefore narrow and elongated, with very steep rocky sides (Fig. 6). In less favorable glacial periods, there was a cessation of tufa deposition and a renewed increased erosion and incision. In more favorable, interglacial periods, tufa and lakes formation in the valley occurred again. One such period continues today. Today, however, this process is increasingly threatened by either direct or even more indirect human impact (e.g. climate change) and there is an increasing danger to the survival of this very fragile natural balance.

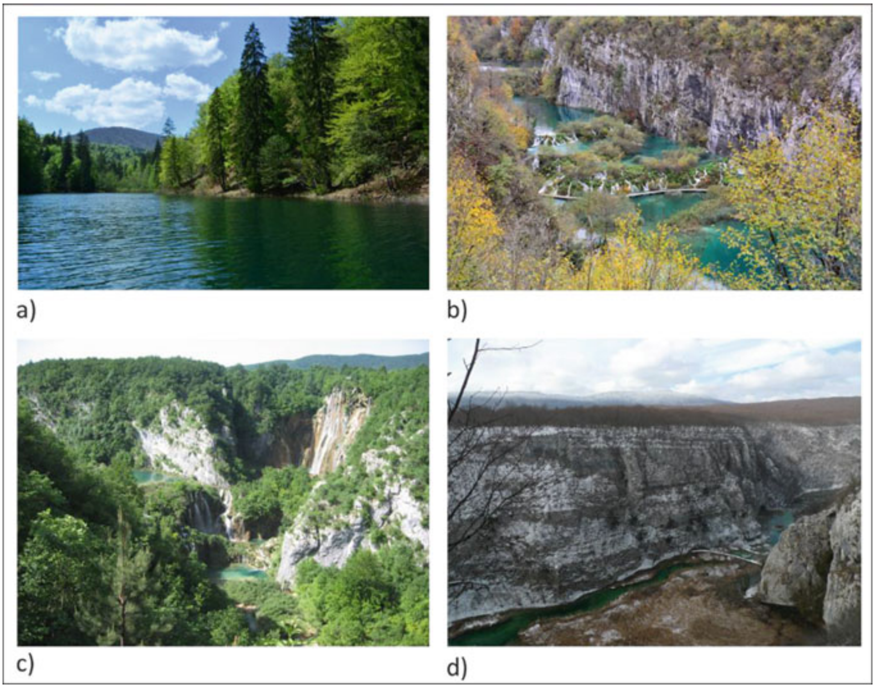

Fig. 6 **a** The shores of Prošćansko Lake formed in dolomite (photo: N. Bočić), **b** The Lower lakes were formed by immersing a deeply incised canyon in a limestone base due to rising of tufa barriers (photo: K. Bočić), **c** Sastavci—by merging water from the Lower Lakes and water of the Plitvice stream, which falls down a 76 m high waterfall, begins today's course of the river Korana (photo: N. Bočić), **d** the canyon of the river Korana incised into a limestone plateau (photo: H. Cvitanović)

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Hydrology, Hydrogeology and Hydromorphology of the Plitvice Lakes Area

Ivan Čanjevac, Ivan Martinić, Maja Radišić, Josip Rubinić, and Hrvoje Meaški

Abstract The Plitvice Lakes where the first place in Europe to be included in the UNESCO World Natural Heritage List as a phenomenon that is created primarily by water. The main phenomenon of the National Park is a series of barrage lakes created by the growth of tufa barriers on the old riverbed of the Korana River. In addition, the highest waterfall in Croatia, 78 m high Veliki slap Waterfall is one of the main attractions. In this chapter, main hydrological, hydrogeological and hydromorphological characteristics of the Plitvice Lakes National Park are presented. Basic climatological components are analysed following data on groundwater storage and circulation. Final part of the chapter is dedicated to surface water, i.e. streams and lakes of the Plitvice Lakes area, their basic hydrological characteristics and hydromorphological status according to the Water Framework Directive.

Keywords Hydrology · Hydrogeology · Hydromorphology · Karst · Barrage lake · Water balance · Discharge regime · Climate change

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1 Introduction

Because of its exceptional natural values and beauty, the Plitvice Lakes area was legally protected already in 1928 and declared a national park in 1949 as the first national park in Croatia. In 1979 the lakes were included in the UNESCO World Natural Heritage List (Bočić 2009). The lakes were the first place in Europe to be included in the list as a phenomenon that is created primarily by water (Meaški 2011). The main phenomenon of National Park is a series of barrage lakes created by the growth of tufa barriers on the old riverbed of the Korana River (Bočić 2009). In addition, the highest waterfall in Croatia, 78 m high Veliki slap Waterfall is one of the main attractions. Plitvice Lakes National Park (PLNP) is located in the karst area of the Croatian highlands, on the border of the Lika and Kordun regions, and the Ogulin-Plaški valley. The area is predominantly hilly-mountainous. Mala Kapela Massif with its highest peak Seliški vrh (1279 m a.s.l.) dominates the southwestern half of the park. The northeastern part of the park is of lower altitude, down to about 360 m a.s.l. in the canyon of the Korana River (Fig. 1). The Plitvice Lakes belong to the Danube catchment area, i.e., to the Black Sea basin, and they are situated in the boundary area towards the Adriatic Sea basin, with the watershed divide crossing the Park in the area of Babin potok. According to current findings, the entire Plitvice Lakes catchment area is within the boundaries of the Park, except for small surfaces in the mountain area of Mala Kapela and area between Kuselj and Saborsko (PLNP Management Plan 2019).

Dolostones and limestones of Mesozoic age form the greater part of the geological base of the park. The southwestern part of the park consists of limestones and dolostones of Jurassic age. The area is filled with dolines and caves, indicators of a well-developed karst. The central part of the park is built on Upper Triassic dolomite rocks with low permeability. From here flow the Bijela rijeka Stream and the Crna rijeka Stream whose waters form the Matica River and the Plitvice Lakes system. The northeastern part of the park consists of Upper Cretaceous limestones, which are strongly karstified.

Such a lithological composition of the area indicates the presence of a developed network of groundwater flows. Comparing the topographic and hydrogeological watersheds of the Plitvice Lakes (Fig. 2), we can see that they are largely different. The hydrogeological watershed of the Plitvice Lakes system (including the Plitvica Stream) occupies about 152 km^2 (Meaški 2011), while the topographic watershed covers only 72 km^2. It is important to note that water not only enters the lake system through underground routes but is also lost through them.

Data from the National habitat map (2016) where used to analyze land cover. 83.5% of the park area is covered with forest. Only 1.12% of the area is covered with water, 0.93% cover the lakes and perennial streams, while intermittent streams cover 0.19% of the park. The rest of the area is covered with scattered patches of meadows, pastures, transitional areas, abandoned agricultural land and settlements.

Administratively, the park is divided between 2 counties (Karlovac county and Lika-Senj county) and within them 4 municipalities and 20 settlements. According

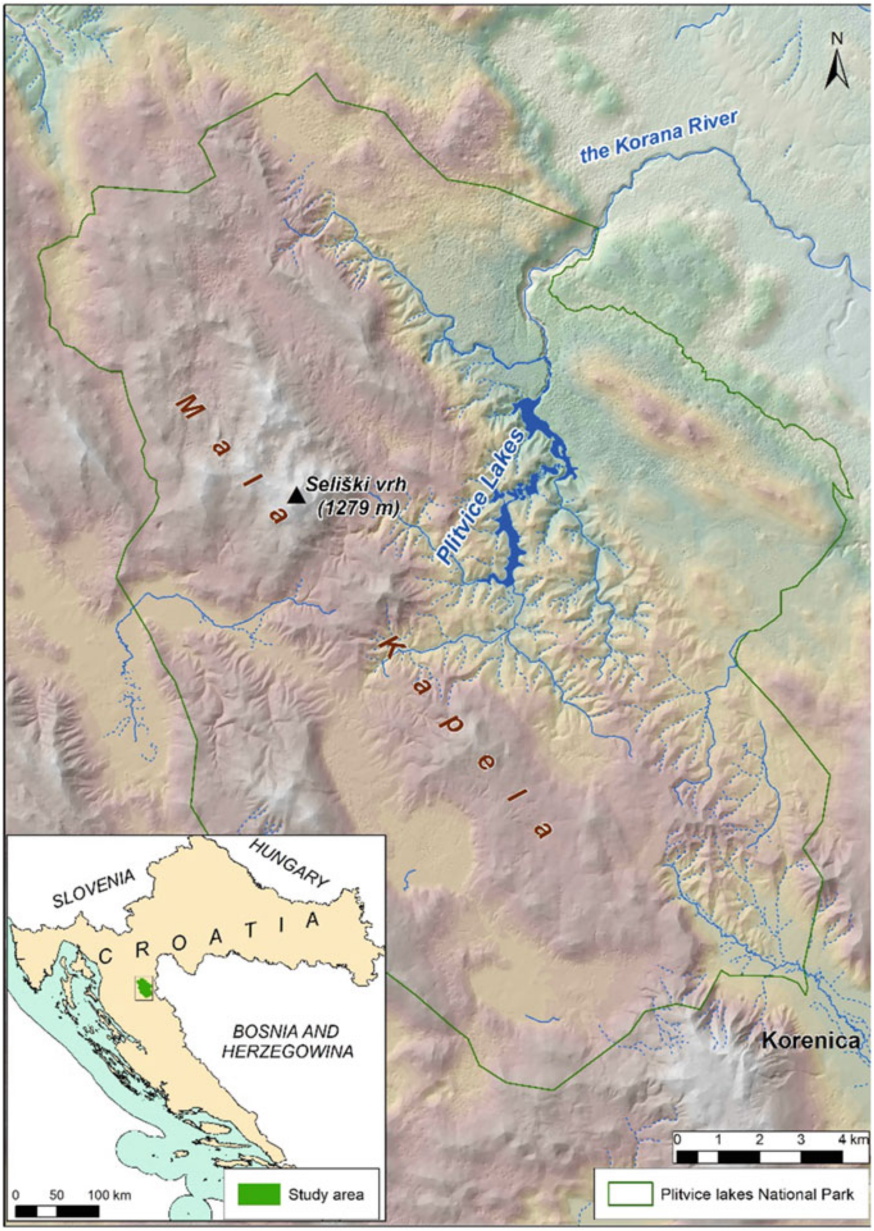

Fig. 1 Position of the Plitvice Lakes National Park

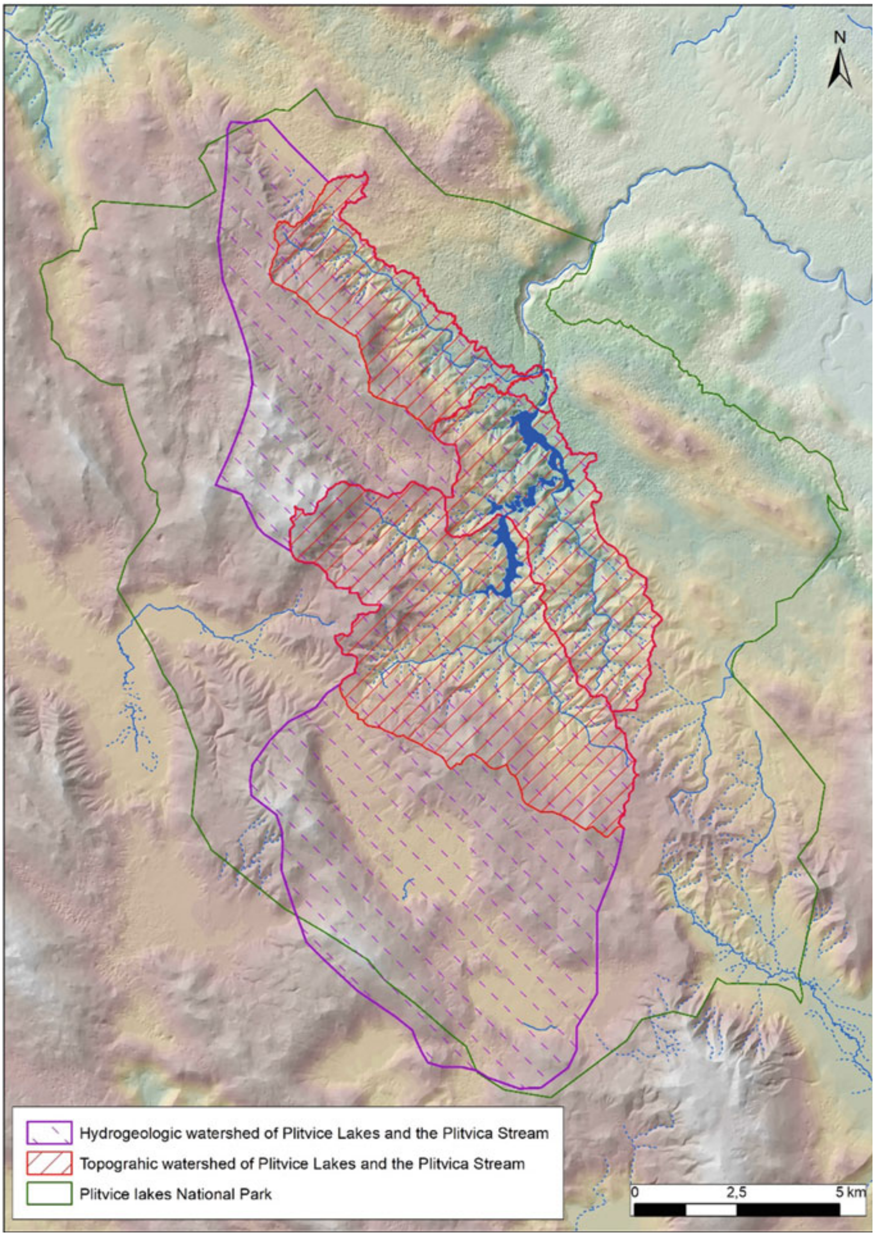

Fig. 2 Comparison of hydrogeological and topographical watershed of the Plitvice Lakes

to the 2011 census, 1411 inhabitants live in the National Park, whose total area is 296 km^2. The largest settlements, Plitvička Jezera and Jezerce, have about 300 inhabitants (PLNP Management Plan 2019). Most of the settlements are located along the two main roads D1 and D52.

According to the work of Rubinić et al. (2008), and Bencetić Klaić et al. (2018), the first cartographic records with the toponym Plitvice Lakes appear in the seventeenth century, while the first textual records date from the eighteenth century. Greater attention was paid to the lakes in 1850, when a more detailed map was produced, a geological survey was conducted, first depths of lakes were measured, which is considered the first limnological work on the lakes (Franić 1910). The first comprehensive limnological survey was carried out by Gavazzi (1919). A significant turning point occurred in 1951, when for the first time a multidisciplinary scientific research project was organized at the Plitvice Lakes by a team led by Petrik (1958), and continuous hydrological monitoring of water level fluctuations in the lakes and flow at the sites of individual tributaries in the lake system as well as on the outflow of lakes began.

In 2003, research began in the Plitvice Lakes and in the wider region within the framework of the international project "Investigation of post-war anthropogenic pollution and the definition of protective measures for the Plitvice Lakes National Park and the Bihać region in the border area between Croatia and Bosnia and Herzegovina" (Anthroprol.prot 2006), within which the analysis of water exchange dynamics was carried out (Babinka 2007).

The hydrogeological project "Sustainable water use in the Plitvice Lakes pilot area" analyzed surface and groundwater phenomena in Plitvice Lakes, as well as hydrological and hydrogeological relationships between them (Biondić et al. 2009, 2010; Meaški 2011).

The hydrology of Plitvice Lakes is also addressed by Riđanović (1989) who brought first analyzes of hydrological data from gauging stations operating since the beginning of 1980s. Bonacci (2000, 2013a, b), was first to point out the problem of pronounced decreasing runoff trends, and Beraković (2005) analyzed the water balance of the Plitvice Lakes. In the work of Zwicker and Rubinić (2005), the trends of the course of water level and flow fluctuations were analyzed, and the average growth of tufa barriers was estimated, and in the work of Rubinić et al. (2008) and Rubinić and Zwicker Kompar (2009), the hydrological relationships between the hydrological elements of individual lakes were analyzed. In the 2016–2021 period an interdisciplinary project Hydrodynamics of Plitvice Lakes is organized by the Faculty of Science in Zagreb, the Faculty of Civil Engineering in Rijeka and the Faculty of Geotechnical Engineering in Varaždin.

Following the acceptance and gradual implementation of the Water Framework Directive in Croatia contemporary hydromorphological analyzes where carried out in the PLNP. The research on hydromorphogical pressures and state of Lakes Prošće and Kozjak were done by interdisciplinary team from the University of Zagreb, Faculty of Science, Department of Geography and private company Elektroprojekt Consulting